ORBITAL MOMENTUM EFFECTS DUE TO A LIQUID NATURE OF TRANSIENT STATE

S.M. Troshin and N.E. Tyurin

Institute for High Energy Physics, 142281, Protvino, Moscow Region, Russia

Abstract

It is argued that directed flow v_1, the observable introduced for description of nucleus collisions, can be used for the detection of the nature of state of the matter in the transient state of hadron and nuclei collisions. We consider a possible origin of the directed flow in hadronic reactions as a result of rotation of the transient matter and trace analogy with nucleus collisions. Our proposal it that the presence of directed flow can serve as a signal that transient matter is in a liquid state.

Important tools in the studies of the nature of the new form of matter are the anisotropic flows which are the quantitative characteristics of the collective motion of the produced hadrons in the nuclear interactions. With their measurements one can obtain a valuable information on the early stages of reactions and observe signals of QGP formation. The experimental probes of collective dynamics in AA interactions, the momentum anisotropies v_n are defined by means of the Fourier expansion of the transverse momentum spectrum over the momentum azimuthal angle ϕ. The angle ϕ is the angle of the detected particle transverse momentum with respect to the reaction plane spanned by the collision axis z and the impact parameter vector $\mathbf{b}$ directed along the x axis. Thus, the anisotropic flows are the azimuthal correlations with the reaction plane. In particular, the directed flow is defined as

$$v_1(p_\perp) \equiv \langle \cos\phi \rangle_{p_\perp} = \langle p_x/p_\perp \rangle = \langle \hat{\mathbf{b}} \cdot \mathbf{p}_\perp / p_\perp \rangle \tag{1}$$

From Eq. (1) it is evident that this observable can be used for studies of multiparticle production dynamics in hadronic collisions provided that impact parameter $\mathbf{b}$ is fixed.

We assume that the origin of the transient state and its dynamics along with hadron structure can be related to the mechanism of spontaneous chiral symmetry breaking (χSB) in QCD, which leads to the generation of quark masses and appearance of quark condensates. This mechanism describes transition of the current into constituent quarks. The gluon field is considered to be responsible for providing quarks with masses and its internal structure through the instanton mechanism of the spontaneous chiral symmetry breaking. Massive constituent quarks appear as quasiparticles, i.e. current quarks and the surrounding clouds of quark–antiquark pairs which consist of a mixture of quarks of the different flavors. Quark radii are determined by the radii of the surrounding clouds. Quantum numbers of the constituent quarks are the same as the quantum numbers of current quarks due to conservation of the corresponding currents in QCD.

Collective excitations of the condensate are the Goldstone bosons and the constituent quarks interact via exchange of the Goldstone bosons; this interaction is mainly due to

pion field. Pions themselves are the bound states of massive quarks. The interaction responsible for quark-pion interaction can be written in the form [1]:

$$\mathcal{L}_I = \bar{Q}[i\partial\!\!\!/ - M\exp(i\gamma_5\pi^A\lambda^A/F_\pi)]Q, \quad \pi^A = \pi, K, \eta. \tag{2}$$

The interaction is strong, the corresponding coupling constant is about 4. The general form of the total effective Lagrangian ($\mathcal{L}_{QCD} \to \mathcal{L}_{eff}$) relevant for description of the non–perturbative phase of QCD includes the three terms [2]

$$\mathcal{L}_{eff} = \mathcal{L}_\chi + \mathcal{L}_I + \mathcal{L}_C.$$

Here $\mathcal{L}_\chi$ is responsible for the spontaneous chiral symmetry breaking and turns on first. The picture of a hadron consisting of constituent quarks embedded into quark condensate implies that overlapping and interaction of peripheral clouds occur at the first stage of hadron interaction. The interaction of the condensate clouds assumed to of the shock-wave type, this condensate clouds interaction generates the quark-pion transient state. This mechanism is inspired by the shock-wave production process proposed by Heisenberg long time ago. At this stage, part of the effective lagrangian $\mathcal{L}_C$ is turned off (it is turned on again in the final stage of the reaction). Nonlinear field couplings transform then the kinetic energy to internal energy. As a result the massive virtual quarks appear in the overlapping region and transient state of matter is generated. This state consist of $\bar{Q}Q$ pairs and pions strongly interacting with quarks. This picture of quark-pion interaction can be considered as an origin for percolation mechanism of deconfinement resulting in the liquid nature of transient matter [3].

Part of hadron energy carried by the outer condensate clouds being released in the overlap region goes to generation of massive quarks interacting by pion exchange and their number was estimated as follows as follows:

$$\tilde{N}(s,b) \propto \frac{(1-\langle k_Q\rangle)\sqrt{s}}{m_Q}\, D_c^{h_1} \otimes D_c^{h_2} \equiv N_0(s)D_C(b), \tag{3}$$

where m_Q – constituent quark mass, $\langle k_Q\rangle$ – average fraction of hadron energy carried by the constituent valence quarks. Function D_c^h describes condensate distribution inside the hadron h and b is an impact parameter of the colliding hadrons. Thus, $\tilde{N}(s,b)$ quarks appear in addition to $N = n_{h_1} + n_{h_2}$ valence quarks.

The generation time of the transient state Δt_{tsg} in this picture obeys to the inequality

$$\Delta t_{tsg} \ll \Delta t_{int},$$

where Δt_{int} is the total interaction time. The newly generated massive virtual quarks play a role of scatterers for the valence quarks in elastic scattering; those quarks are transient ones in this process: they are transformed back into the condensates of the final hadrons.

Under construction of the model for elastic scattering it was assumed that the valence quarks located in the central part of a hadron are scattered in a quasi-independent way off the transient state with interaction radius of valence quark determined by its inverse mass:

$$R_Q = \kappa/m_Q. \tag{4}$$

The elastic scattering S-matrix in the impact parameter representation is written in the model in the form of linear fractional transform:

$$S(s,b) = \frac{1+iU(s,b)}{1-iU(s,b)}, \tag{5}$$

where $U(s,b)$ is the generalized reaction matrix, which is considered to be an input dynamical quantity similar to an input Born amplitude and related to the elastic scattering scattering amplitude through an algebraic equation which enables one to restore unitarity. The function $U(s,b)$ is chosen in the model as a product of the averaged quark amplitudes

$$U(s,b) = \prod_{Q=1}^{N} \langle f_Q(s,b)\rangle \tag{6}$$

in accordance with assumed quasi-independent nature of the valence quark scattering. The essential point here is the rise with energy of the number of the scatterers like $\sqrt{s}$. The b–dependence of the function $\langle f_Q\rangle$ has a simple form $\langle f_Q(b)\rangle \propto \exp(-m_Q b/\xi)$.

These notions can be extended to particle production with account of the geometry of the overlap region and properties of the liquid transient state. Valence constituent quarks would excite a part of the cloud of the virtual massive quarks and those quark droplets will subsequently hadronize and form the multiparticle final state. This mechanism can be relevant for the region of moderate transverse momenta while the region of high transverse momenta should be described by the excitation of the constituent quarks themselves and application of the perturbative QCD to the parton structure of the constituent quark. The model allow to describe elastic scattering and the main features of multiparticle production. In particular, it leads to asymptotical dependencies

$$\sigma_{tot,el} \sim \ln^2 s, \quad \sigma_{inel} \sim \ln s, \quad \bar{n} \sim s^{\delta}. \tag{7}$$

The geometrical picture of hadron collision at non-zero impact parameters described above implies that the generated massive virtual quarks in overlap region will obtain large initial orbital angular momentum at high energies. The total orbital angular momentum can be estimated as follows

$$L(s,b) \simeq \alpha b \frac{\sqrt{s}}{2} D_C(b). \tag{8}$$

The parameter α is related to the fraction of the initial energy carried by the condensate clouds which goes to rotation of the quark system and the overlap region, which is described by the function $D_C(b)$, has an ellipsoidal form. It should be noted that $L \to 0$ at $b \to \infty$ and $L = 0$ at $b = 0$. At this point we would like to stress again on the liquid nature of transient state. Namely due to strong interaction between quarks in the transient state, it can be described as a quark-pion liquid. Therefore, the orbital angular momentum L should be realized as a coherent rotation of the quark-pion liquid as a whole in the xz-plane (due to mentioned strong correlations between particles presented in the liquid). It should be noted that for the given value of the orbital angular momentum L kinetic energy has a minimal value if all parts of liquid rotates with the same angular velocity. We assume therefore that the different parts of the quark-pion liquid in the overlap region indeed have the same angular velocity ω. In this model spin of the polarized hadrons has its origin in the rotation of matter hadrons consist of. In contrast, we assume rotation of

the matter during intermediate, transient state of hadronic interaction. Collective rotation of the strongly interacting system of the massive constituent quarks and pions is the main point of the proposed mechanism of the directed flow generation in hadronic and nuclei collisions. We concentrate on the effects of this rotation and consider directed flow for the constituent quarks supposing that directed flow for hadrons is close to the directed flow for the constituent quarks at least qualitatively. The assumed particle production mechanism at moderate transverse momenta is an excitation of a part of the rotating transient state of massive constituent quarks (interacting by pion exchanges) by the one of the valence constituent quarks with subsequent hadronization of the quark-pion liquid droplets. Due to the fact that the transient matter is strongly interacting, the excited parts should be located closely to the periphery of the rotating transient state otherwise absorption would not allow to quarks and pions to leave the region (quenching). The mechanism is sensitive to the particular rotation direction and the directed flow should have opposite signs for the particles in the fragmentation regions of the projectile and target respectively. It is evident that the effect of rotation (shift in p_x value) is most significant in the peripheral part of the rotating quark-pion liquid and is to be weaker in the less peripheral regions (rotation with the same angular velocity ω), i.e. the directed flow v_1 (averaged over all transverse momenta) should be proportional to the inverse depth Δl where the excitation of the rotating quark-pion liquid takes place. The geometrical picture of hadron collision has an apparent analogy with collisions of nuclei and it should be noted that the appearance of large orbital angular momentum should be expected in the overlap region in the non-central nuclei collisions. And then due to strongly interacting nature of the transient matter we assume that this orbital angular momentum realized as a coherent rotation of liquid. Thus, it seems that underlying dynamics could be similar to the dynamics of the directed flow in hadron collisions.

We can go further and extend the production mechanism from hadron to nucleus case also. This extension cannot be straightforward. First, there will be no unitarity corrections for the anisotropic flows and instead of valence constituent quarks, as a projectile we should consider nucleons, which would excite rotating quark liquid. Of course, those differences will result in significantly higher values of directed flow. But, the general trends in its dependence on the collision energy, rapidity of the detected particle and transverse momentum, should be the same. In particular, the directed flow in nuclei collisions as well as in hadron reactions will depend on the rapidity difference $y - y_{beam}$ and not on the incident energy. The mechanism therefore can provide a qualitative explanation of the incident-energy scaling of v_1 observed at RHIC [4].

References

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